

Cluster Hadronization in HERWIG 5.9

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Abstract: The HERWIG 5.9 cluster hadronization model is briefly discussed here. It is shown that the model has peculiar behaviour when new heavy baryon resonances are included in the HERWIG 5.9 particle table. New fragmentation model is proposed to cure this problem and simple tuning of HERWIG 5.9 with this new model has been made using event shapes variables and identified particle momentum spectra in e^+e^- interactions at LEPI. Finally, the predictions of the two hadronization models are compared.

1 Introduction

Fragmentation of quarks and gluons into hadrons is a typical non-perturbative phenomenon and phenomenological methods must be used to model it. The three basic models are available at present: independent fragmentation (ISAJET, [1]), string fragmentation (JETSET, [2]), and cluster hadronization (HERWIG, [3]).

The independent fragmentation model does not take into account the colour connections and it is also less successful than other two models. The concept of colour connection is essential for the string and cluster hadronization models. JETSET gives better agreement with the experimental data than HERWIG but also contains a large number of parameters which can be tuned. Nevertheless, HERWIG, with its few-parametric cluster hadronization model, represents main alternative to the string models.

In this paper it is shown that the behaviour of HERWIG 5.9 in relation to the light quark sector (u , d , s) does not correspond to the naive view of cluster hadronization in that the introduction of the new baryon cluster decay channels does not lead to an increase in the predicted proton yield. In fact, the proton multiplicity decreases in comparison to predictions made with the default particle list.

This article reviews the HERWIG 5.9 hadronization model and pins down the origin of the peculiar behaviour. A new hadronization model is proposed to cure the problem. To make reliable comparison between the two models, it was necessary to tune the new one. Finally, the differences between the models are discussed. Wherever possible the names of variables are taken from HERWIG 5.9 notation. They are indicated by `typewriter` font.

This work is important for analyses at the HERA experiments in that a reliable theoretical description of the baryon sector needs to be provided. Although there have so far been very few

experimental results on baryon yield from H1 and ZEUS, interesting observations are already being made on strangeness suppression [4, 5] and baryon number propagation [6] and, with the high statistics now available to the experiments, this will soon become an experimentally productive area.

2 Hadronization in HERWIG 5.9

Colourless clusters are formed from colour connected quarks, [7]. They consist of quark-antiquark (meson-like clusters), quark-diquark (baryon-like), or antiquark-antidiquark (anti-baryon-like) pairs. Only the meson-like clusters can occur in e^+e^- interactions. The basic idea of the model is that the clusters decay according to the phase space available to the decay products.

2.1 HERWIG 5.9 parameters and variables

The most important HERWIG 5.9 parameters and variables relevant to cluster model (subroutine `HWCHAD`) are described in this subsection. The values shown here are the default HERWIG 5.9 settings.

The a priori weights for quarks d, u, s, c, b, t , and diquarks (in that order) are assumed to be equal

$$\text{PWT}(1) = \dots = \text{PWT}(7) = 1. \quad (1)$$

Weights for diquarks of different flavour compositions are also calculated from these and the result is similarly stored in the array `PWT`.

Parameters `CLMAX=3.35` and `CLPOW=2` determine the maximum allowed mass of the cluster

$$M_{max}^{\text{CLPOW}} = \text{CLMAX}^{\text{CLPOW}} + (\text{RMAS}(\text{ID1}) + \text{RMAS}(\text{ID2}))^{\text{CLPOW}}, \quad (2)$$

where `RMAS(ID1)` and `RMAS(ID2)` are masses of the quarks from which the cluster is formed. If the cluster is too heavy it is first cut in two by creation of quark antiquark pair (subroutine `HWCCUT`).

All particles are grouped according to their flavour content and their internal codes `IDHW` are stored in the one-dimensional array `NCLDK`. The first (and also the lightest) hadron of a given flavour (`ID1, ID2`) has position `LOCN(ID1, ID2)` in the array `NCLDK`. The other particles with the same flavour are stored from this position and their number is `RESN(ID1, ID2)`. The masses of the lightest hadrons are put in `RMIN(ID1, ID2)`. Another one-dimensional array `CLDKWT` stores spin weights and mixing weights. For every flavour these weights are normalised by the maximum weight.

Individual weights are stored for all particles in the table `SWTEF`. These weights are set to one in the default HERWIG 5.9 version. There are also parameters that set individual weights for group of particles in HERWIG 5.9, for example `DECWT` is the weight for baryons in decuplet.

2.2 Implementation of cluster hadronization model (HWCHAD)

If the mass $EM0$ of cluster with flavour content $(ID1, ID3)$ is equal to the mass of the lightest hadron with the same flavour then the cluster is identified with this hadron. In the other cases the cluster decays into two hadrons.

To begin with, the channel with the lightest decay products is chosen. If the sum of their masses $(EM1, EM2)$ is bigger than the cluster mass $EM0$ then cluster decays by π^0 emission. In the other cases the phase space $PCMAX$ of this decay is used as a maximum phase space weight

$$PCMAX = \sqrt{EM0^2 - (EM1 + EM2)^2} \cdot \sqrt{EM0^2 - (EM1 - EM2)^2}. \quad (3)$$

The hadronization of the cluster proceeds in the following three steps.

1. The (di)quark anti(di)quark pair of the flavour $ID2$ is created from vacuum according to the probability

$$P_{flavour}(ID2) = PWT(ID2) / \sum_I PWT(I), \quad (4)$$

where the sum is over all allowed flavours.

2. One hadron with flavour $(ID1, ID2)$ is randomly chosen from the iso-flavour table $NCLDK$ and this particle is accepted according to its weight $CLDKWT$. If the particle is not accepted then another hadron with the same flavour content $(ID1, ID2)$ is taken from the table and so on. The corresponding probability that particle $IR1 = NCLDK(I1)$ is chosen is then

$$P_{spin}(IR1|ID1, ID2) = \frac{CLDKWT(I1)}{\sum_{I \in LOCN(ID1, ID2)}^{LOCN+RESN-1} CLDKWT(I)}. \quad (5)$$

The same procedure is applied to the hadrons with flavour $(ID2, ID3)$.

3. Once the decay channel has been chosen it is accepted according to its phase space PCM (given by formula (3)) with probability

$$P_{phase} = \sqrt{SWTEF(IR1)} \cdot \sqrt{SWTEF(IR2)} \cdot PCM / PCMAX. \quad (6)$$

If the decay mode is not accepted the algorithm starts again from the first point (i.e. from creation of quark antiquark pair).

This algorithm gives the following expression for the probability for decay of the given cluster $(ID1, ID3)$ into the hadrons with codes $IR1=NCLDK(I1)$ and $IR2=NCLDK(I2)$

$$P(IR1, IR2, ID2|ID1, ID3) = P_{flavour} \cdot P_{spin}(IR1) \cdot P_{spin}(IR2) \cdot P_{phase}. \quad (7)$$

It is now clear, why the inclusion of some new massive resonances with a given flavour leads to the suppression of all decay channels with the hadrons of the same flavour. Omitting hadron spins and mixing weights, probability (5) depends only on the number of iso-flavour particles

$$P_{spin}(IR1|ID1, ID2) = \frac{1}{RESN(ID1, ID2)}. \quad (8)$$

Finally, the overall probability of a cluster to decay into channels with created flavour ID2 is

$$P(\text{ID2}|\text{ID1}, \text{ID3}) = \sum_{\text{IR1}, \text{IR2}} P(\text{IR1}, \text{IR2}, \text{ID2}|\text{ID1}, \text{ID3}) \\ \propto \text{PWT}(\text{ID2}) \cdot \frac{\sum_{\text{IR1}, \text{IR2}} P_{\text{phase}}}{\text{RESN}(\text{ID1}, \text{ID2}) \cdot \text{RESN}(\text{ID2}, \text{ID3})}, \quad (9)$$

which is nothing else than the **mean** value of phase spaces of the corresponding decay channels. The phase space of resonances is small due to their high masses. Hence, this new resonances lower value of the overall probability (9).

The motivation for the HERWIG authors was to eliminate factor 1/2 in $u\bar{u}$ and $d\bar{d}$ mixing for neutral non-strange mesons, [12]. Indeed, this algorithm gives the same number of π^0 and π^+ in the case where there are only u and d quarks, with no baryons, and with π^0 , π^\pm , and isotopic (η -like) singlet.

This behaviour of HERWIG 5.9 is demonstrated in Tab. 3. Both versions (5.8 and 5.9) have the same default settings but HERWIG 5.9 particle table contains more meson resonances. Consequently, baryon production was enhanced and meson production decreased.

3 New cluster hadronization model

In the rest frame of a particle of mass M , the width of a two-body decay is given, generally, by expression

$$d\Gamma = \frac{1}{32\pi^2} |\mathcal{M}|^2 \frac{|\mathbf{p}_1|}{M^2} d\Omega, \quad (10)$$

where final particles are labeled 1 and 2, \mathcal{M} is the corresponding matrix element, and

$$|\mathbf{p}_1| = |\mathbf{p}_2| = \frac{\left[\left(M^2 - (m_1 + m_2)^2 \right) \left(M^2 - (m_1 - m_2)^2 \right) \right]^{1/2}}{2M} = \frac{\text{PCM}(M, m_1, m_2)}{2M} \quad (11)$$

are the momenta of final state particles.

We do not know a great deal about the matrix element. We can sum over final states (spin factors), we can take into account mixing of flavours (mixing weights) and we can apply Zweig's rule which states the two-body decays of cluster (ID1, ID3) to pair of hadrons with flavour (ID1, ID3) and (ID2, ID2) are strongly suppressed. Assuming that the matrix elements are the same for all decay channels of a cluster and that they depend only on the flavour ID2 of a created (di)quark anti(di)quark pair, the weight $W(\text{IR1}, \text{IR2}, \text{ID2}|\text{ID1}, \text{ID3})$ of particular decay of cluster (ID1, ID3) into hadrons IR1 and IR2 with flavour content (ID1, ID2) and (ID2, ID3) is

$$W(\text{IR1}, \text{IR2}, \text{ID2}|\text{ID1}, \text{ID3}) = \text{PWT}(\text{ID2}) \cdot (2J_1 + 1) \cdot (2J_2 + 1) \cdot \text{WT}(\text{IR1}) \cdot \text{WT}(\text{IR2}) \cdot \\ \cdot \text{SWTEF}(\text{IR1}) \cdot \text{SWTEF}(\text{IR2}) \cdot \text{PCM}(\text{EM0}, \text{EM1}, \text{EM2}), \quad (12)$$

where J_1, J_2 are particle spins and WT is flavour mixing weight.

The overall probability for decay channels with created flavour ID2 is then (again omitting spins, mixing weights, and individual weights SWTEF)

$$P(\text{ID2}|\text{ID1}, \text{ID3}) \propto \text{PWT}(\text{ID2}) \cdot \sum_{\text{IR1}, \text{IR2}} \text{PCM}. \quad (13)$$

Contrary to Eq.(9) this probability is proportional to the **sum** of the phase spaces of particular channels. Therefore, the inclusion of new baryon resonances will enhance the baryon multiplicities.

The new hadronization model is based on formula (12). Several subroutines have been changed to implement this model into HERWIG 5.9 (HWCHAD, HWURES). Moreover, HERWIG 5.9 particle table had to be extended. As was mentioned earlier, there are plenty of meson resonances in the table but only the basic baryon octet and decuplet. New baryon resonances dramatically increase the probability for a cluster decay through the baryon channel and they play an important role in the new model. Hence, I decided to include all light quark meson and baryon resonances that have their own PDG number in [9]. The branching ratios of particular decay modes were taken also from this paper. The properties of these new resonances were put in new subroutine MHWRES.

3.1 Tuning HERWIG 5.9 with new hadronization model

To make final comparison between the both hadronization models, one has to use the tuned settings of HERWIG 5.9 parameters. The L3 fit has been used for the original model (see Tab. 1).

	H5.9	H5.9n	H5.9n
parameter	L3 fit	CAND1	CAND2
QCDLAM	0.177	0.179	0.1602
RMASS(13)	0.75	0.706	0.764
CLMAX	3.006	5.27	3.90
CLPOW	2.033	—	1.53
CLSMR	0.35	—	0.341
DECWT	0.5	—	0.753
PWT(3)	0.88	—	1.071
PWT(7)	0.80	0.812	2.408

Table 1: Settings of HERWIG 5.9 for both hadronization models.

Complete tuning of HERWIG 5.9 with new hadronization model has not been attempted. I used the same method as in [11] but with fewer statistics so the presented results can still be improved. DELPHI measurements of event shape variables [11] and LEPI data of p -spectra of identified particles have been used for tuning the parameters. There are two settings for HERWIG 5.9 with new hadronization (H5.9n) in the Tab. 1. In the case of **CAND1** setting, only four parameters have been tuned. **CAND2** represents the best fit where the same parameters was tuned as in the case of L3 fit. Tab. 2 gives a summary of the fit results.

4 Comparison of the two cluster hadronization models

Although the probability of cluster decay through the particular channel is proportional to the phase space in both cases, the strange normalisation factors of the standard version (see Eq. (5)) give different behaviour of the models.

	Event shapes	Ident. particles	All channels
L3 fit	$\chi^2 = 2874/305 = 9.4$	$\chi^2 = 1002/157 = 6.4$	$\chi^2 = 3876/462 = 8.4$
CAND1	$\chi^2 = 3121/260 = 12.0$	$\chi^2 = 921/130 = 7.1$	$\chi^2 = 4042/390 = 10.5$
CAND2	$\chi^2 = 2319/305 = 7.6$	$\chi^2 = 824/157 = 5.2$	$\chi^2 = 3143/462 = 6.8$

Table 2: Summary of fit results.

CAND1 setting of HERWIG 5.9 is the worst one (see Tab. 2). This could be due to a small number of fitted parameters. Nevertheless, one can find quite a good agreement with the identified particle multiplicities data in the basic meson and baryon octet, Tab. 3.

On the other hand, **CAND2** gives a better description of the data than the HERWIG 5.9 default model with the **L3** setting. The set of fitted parameters was the same, so it is more appropriate to compare these two settings. Since the **L3** fit was made on slightly different data some inconsistency still survives.

Concerning identified particle multiplicities, **CAND1** predictions are in an excellent agreement with the data in the whole meson sector except η' and Φ . Good agreement is also found in the basic baryon octet (except Ξ^-) but large discrepancies occur in the basic baryon decuplet ($\Sigma(1385)$ and $\Xi(1530)^0$).

The situation is roughly the same in the case of **CAND2** set. The agreement with the data is slightly worst (especially for K^0 and K^\pm) and the problems with baryon resonances were not cured although parameter **DECWT** was also tuned in this fit.

The default HERWIG 5.9 hadronization model (**L3** fit) has similar problems in describing the data here. Moreover, it underestimates the production of protons and Λ particles.

Both hadronization models give (within the experimental uncertainties) the correct particle multiplicities for the lightest non-strange mesons and baryons (π , η , ρ , ω , p , Δ) although the new model predictions are slightly closer to the data. The discrepancies occur for the singlet mesons η' and $\Phi(1020)$ and for heavy strange baryons.

5 Conclusions

It has been observed that with the introduction of new nucleon resonances, HERWIG 5.9 predicts a reduced proton yield, contrary to the naive view of cluster hadronization. In the HERWIG 5.9 hadronization scheme, a decay of a colourless cluster takes place in such a way as to eliminate the factor $1/2$ in $u\bar{u}$ and $d\bar{d}$ mixing. The algorithm, however, gives the probability of a cluster decay through channels with a created particular flavour that is proportional to the mean value of corresponding phase spaces.

A new hadronization model which treats all decay channels in the same way has been proposed. It was found that this provides an improved description of inclusive particle data taken by the LEP experiments. In particular, the baryon sector is better described than with the default version of HERWIG 5.9. This is a particularly important if the HERWIG model is to be used predictively in HERA environment, in which topics such as baryon number propagation and strange diquark suppression are starting to be studied.

Particle	PDG'98	H5.8	H5.8	H5.9	H5.9	H5.9n	H5.9n
		Delphi	DEF	DEF	L3	CAND	CAND
		FIT			FIT	ONE	TWO
charged	$21.05 \pm 0.20^{[8]}$	20.81	21.17	20.62	21.13	21.03	21.52
π^0	9.42 ± 0.56	9.79	9.76	10.14	10.88	9.51	9.74
π^\pm	17.1 ± 0.4	17.64	17.52	16.7	17.62	17.26	17.53
K^0	2.013 ± 0.033	2.03	2.29	1.937	1.949	1.981	2.253
K^\pm	2.39 ± 0.12	2.11	2.40	2.10	2.20	2.32	2.54
η	0.97 ± 0.10	1.01	1.01	0.92	1.01	0.79	0.89
η'	0.222 ± 0.040	0.14	0.144	0.140	0.157	0.109	0.125
$\rho(770)^0$	1.28 ± 0.14	1.43	1.32	1.16	1.29	1.12	1.12
$K^*(892)^0$	0.747 ± 0.028	0.75	0.796	0.521	0.565	0.640	0.734
$\Phi(1020)$	0.109 ± 0.007	0.099	0.120	0.181	0.178	0.208	0.182
$\omega(782)$	1.10 ± 0.13	0.92	1.10	1.05	1.23	1.00	1.02
p	0.964 ± 0.102	0.77	0.948	1.41	0.77	0.959	0.944
Λ	0.372 ± 0.009	0.367	0.431	0.598	0.256	0.363	0.389
Σ^-	0.071 ± 0.018	0.058	0.066	0.10	0.069	0.082	0.092
Ξ^-	0.0258 ± 0.0010	0.048	0.052	0.070	0.0242	0.0195	0.0208
Δ^{++}	0.085 ± 0.014	0.158	0.198	0.276	0.109	0.113	0.100
$\Sigma(1385)^\pm$	0.0462 ± 0.0028	0.118	0.15	0.20	0.069	0.0713	0.0617
$\Xi(1530)^0$	0.0055 ± 0.0005	0.026	0.024	0.037	0.0053	0.0120	0.0091
Ω^-	0.0016 ± 0.0003	0.0074	0.0078	0.0094	0.0009	0.0019	0.0011
$\Lambda(1520)$	$0.0213 \pm 0.0028^{[8]}$	—	—	—	—	0.0426	0.0339

Table 3: Particle multiplicities per event in e^+e^- interactions at $\sqrt{s} = 91.2$ GeV in the data [10] compared with HERWIG 5.8 (H5.8), HERWIG 5.9 prediction for default cluster hadronization model (H5.9), and for new hadronization model (H5.9n).

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